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14. ABSTRACT
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The technology qualification program verified performance and scalability and then continued to mitigate a few technical risks, particularly those associated with the presence of water in the pressurant gas, especially when used in the liquid oxygen tank. In 2005, testing with a Tridyne system at nearly full-scale size for a flight vehicle application confirmed expectations and indicated that water remaining within the pressurant during the course of the flight duration should pose no problems for a single burn, expendable vehicle application. For multiple burns or for reusable applications, it would likely be necessary to employ a desiccant or some other means to prevent introduction of water into the cryogenic tanks.

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Development and Optimization of a Tridyne Pressurization System for Pressure Fed Launch Vehicles

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Abstract

Over the recent years, Microcosm has been pursuing the development of a Tridyne-based pressurization system and its implementation in the Scorpius family of launch vehicles to obtain substantial gain in payload to orbit. This technology program was initiated with an IR&D program and matured with contracts from the National Reconnaissance Office (NRO), and the Air Force Research Laboratory (AFRL).

The Tridyne pressurization system functions by mixing small amounts of hydrogen and oxygen with the pressurant gas (typically helium). When the mixture is passed through a catalyst bed, the hydrogen and oxygen react to produce heat. The result is hot pressurant gas, with a small amount of water vapor remaining from the combustion process. The implementation scheme developed for the Scorpius family of launch vehicles involves returning some of the heat to the Tridyne mixture in the pressurant tank by means of an internal heat exchanger. This offsets the expansion cooling such that the temperature of the pressurant actually rises as the pressurant is used. The remaining energy is used to elevate the temperature of the gas delivered to the propellant tanks to near the maximum allowable operating temperature of the downstream components (typically about 200 to 250 deg F) such as the regulator and the composite over-wrapped propellant tanks. The result of heating the helium in this way was shown to reduce the mass and volume of required helium and the associated tankage by nearly 50%, resulting in substantial payload gain.

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I. Background

For over 12 years, Microcosm has been involved in the development of the enabling technologies[1] as part of the design and development effort for the low-cost, responsive, pressure-fed expendable launch vehicles.[2,3] The technology effort includes the development of the Tridyne-based High Performance Pressurization System (HPPS), low-cost ablative engines, the high performance light-weight all-composite propellant tanks. The family of launch vehicles in the Scorpius family currently under development for defense and commercial applications is shown in Figure 1 and includes two suborbital vehicles that have been flown successfully and other orbital vehicles in development with capabilities ranging from 700 lbm to 50,000 lbm to Low Earth Orbit (LEO) and Geo Transfer Orbit (GTO) applications.

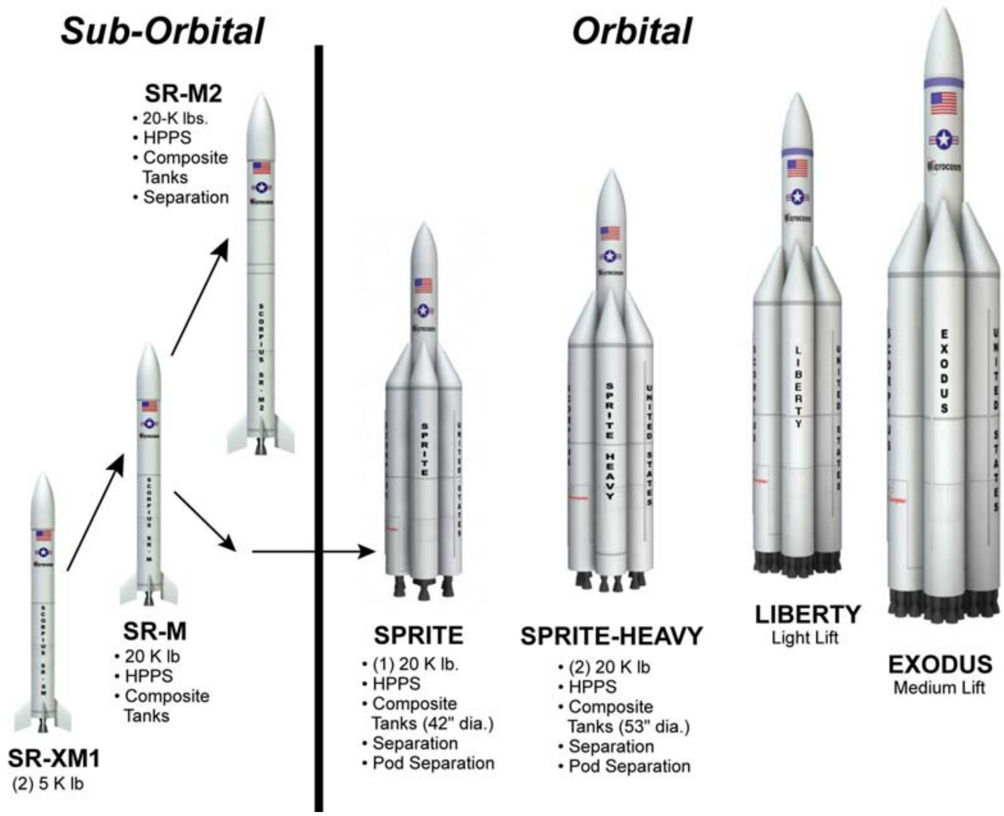

Figure 1. Microcosm's Family of Low-cost, pressure-fed Launch Vehicles

Benefits of heated pressurization systems

Heated, as opposed to cold gas, pressurization systems are particularly advantageous for pressure fed launch vehicles for several reasons. Firstly, the pressurization system for a pressure fed vehicle must be much larger than for a pump fed vehicle, since the propellant tanks will normally be operated at several hundred psi. Consequently, any fractional improvements in pressurization system performance that can reduce pressurant storage requirements will have greater total weight savings for the pressure fed vehicle.

Furthermore, because of the high propellant tank pressure requirement, the minimum pressurant tank pressure at mission completion is relatively high. Due to expansion cooling, this yields a relatively large quantity of unusable pressurant remaining in the pressurant tank for a cold gas system.

Analytical approach for evaluating benefits of heated pressurization systems

Clearly, to achieve the greatest benefits of a heated pressurization system, the system must possess the following characteristics:

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1) Deliver hot pressurant gas to the propellant tank ullage (consistent with limitations in propellant tank materials and pressurization system components)
2) Maintain the propellant tank ullage in a hot, stratified condition (via proper diffuser design)
3) Add heat to the pressurant tank during the expansion process to offset expansion cooling (or, better yet, raise the temperature of the pressurant tank contents as the pressurant is extracted)

To analyze the benefits of a heated pressurization system over a cold gas pressurization system, an analytical modeling process was developed using a combination of commercially available and "home-brew" software packages. The basic system configuration for analysis purposes is shown in Figure 2.

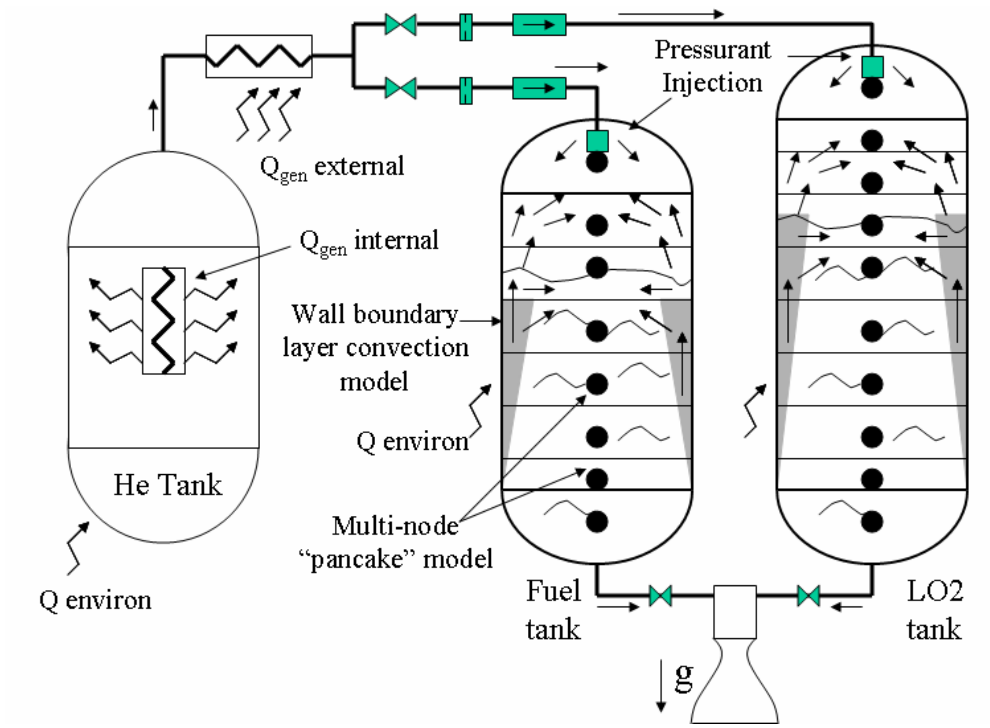

Figure 2. Description of thermal/flow performance model

The analytical model employs Sinda-Fluint to model flow-path and general heat transfer processes, running in conjunction with the Vasquez thermodynamics code to model tank thermodynamics and pressurization control. The Vasquez code was developed in the late 1990's and validated with Boeing Delta III ground testing and flight data. The Vasquez code employs an ullage and liquid multi-node "pancake" model of the propellant tanks in addition to a wall boundary layer convection model to simulate heat transfer between the tank walls, the ullage gas, and the liquid. The Sinda model includes heat transfer characteristics through the tank wall, external tank convective heat transfer, and heat capacity of the graphite-epoxy composite tanks. Additional detailed modeling of the pressurant tank convection and the propellant tank diffusers is performed using Fluent to assure that these components perform as predicted by the simplified (and somewhat more empirical) enhanced 1-dimensional models used in the Sinda-Fluint and Vasquez tools.

The combined analytical model shown in Figure 2 allows general modeling of any of the cold or heated pressurization systems currently of interest. A baseline cold pressurization system is modeled by setting the generated internal and external heat sources (Q_{gen} internal and Q_{gen} external) to zero. A case where only external heat addition is applied is performed by setting the external heat source as required to obtain the desired pressurant gas temperature to the propellant tanks, while the pressurant tank is left to undergo expansion cooling. The internal heat source can be specified to maintain pressurant tank contents at initial temperature. And finally, the pressurant tank can be loaded with chilled gas and the internal heat source specified to raise the pressurant tank contents to some maximum value at the end of mission.

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Summary of trade study results

Table 1 summarizes the modeling assumptions used to evaluate the advantages of two heated pressurization systems compared to a baseline cold gas system.

Table 1. Summary of modeling conditions

	Cold pressurization system	**Heated helium, ambient start**	**Heated helium, chilled start**
Initial helium temp	530 R (70 F)	530 R (70 F)	360 R (-100 F)
Initial helium press	5600 psia	5600 psia	5600 psia
Heat addition to helium tank (Q_{gen} internal)	0	110 BTU/sec	121 BTU/sec
Final helium press	1000 psia	1000 psia	1000 psia
Temp of helium delivered to propellant tanks (via Q_{gen} external)	Tracks pressurant tank mean temperature (Q_{gen} external = 0)	660 R (200 F)	660 R (200 F)
Propellant tank operational pressure	550 psia	550 psia	550 psia

For all cases the initial helium pressure is limited to 5600 psi (based on a viable upper limit for the pressurant tank and other components) and the final helium pressure is set to 1000 psi (allowing ample pressure reserve to maintain propellant tank pressure with system pressure drops). The pressurant tank volume is then iterated to achieve the desired final pressure after 50 lbm of helium has been expelled from the pressurant system.

The cold pressurization system delivers helium to the propellant tanks at a varying temperature equal to the pressurant tank temperature, which drops throughout usage. For both heated systems, heat is applied to the pressurant prior to entering the propellant tanks to maintain the supplied pressurant at 660 R (200 F).

Figure 3 (a, b, and c) shows the comparative results of these three cases: a) A cold pressurization system, b) a heated pressurization with ambient start where the pressurant tank is maintained near ambient temperature, and c) a heated pressurization with chilled start where the pressurant tank temperature is raised during pressurization. Figure 3 clearly illustrates the reduction in pressurant tank volume that can be achieved with a heated system. For a cold gas system (Figure 3.a) , 19.7 ft^3 of tank volume is required to deliver 50 lbm of usable pressurant, and 27.6 lbm remains in the pressurant tank at very low temperature as unusable. With heat application to the tank contents sufficient to just balance expansion cooling (Figure 3b), the tank volume is reduced to 15.5 ft^3 to deliver 50 lbm of pressurant, and only 10.8 lbm remains as unusable. Finally, if the tank is loaded with chilled pressurant at -100 F, and then heated to +70 F as the helium is extracted (Figure 3.c), only 9.8 ft^3 of tank volume is required, with unusable residuals reduced to 6.9 lbm. It may be noted that, for the same amount of delivered helium, the heated system with chilled start allows the helium tank volume to be reduced by a factor of 2 compared to the cold gas system.

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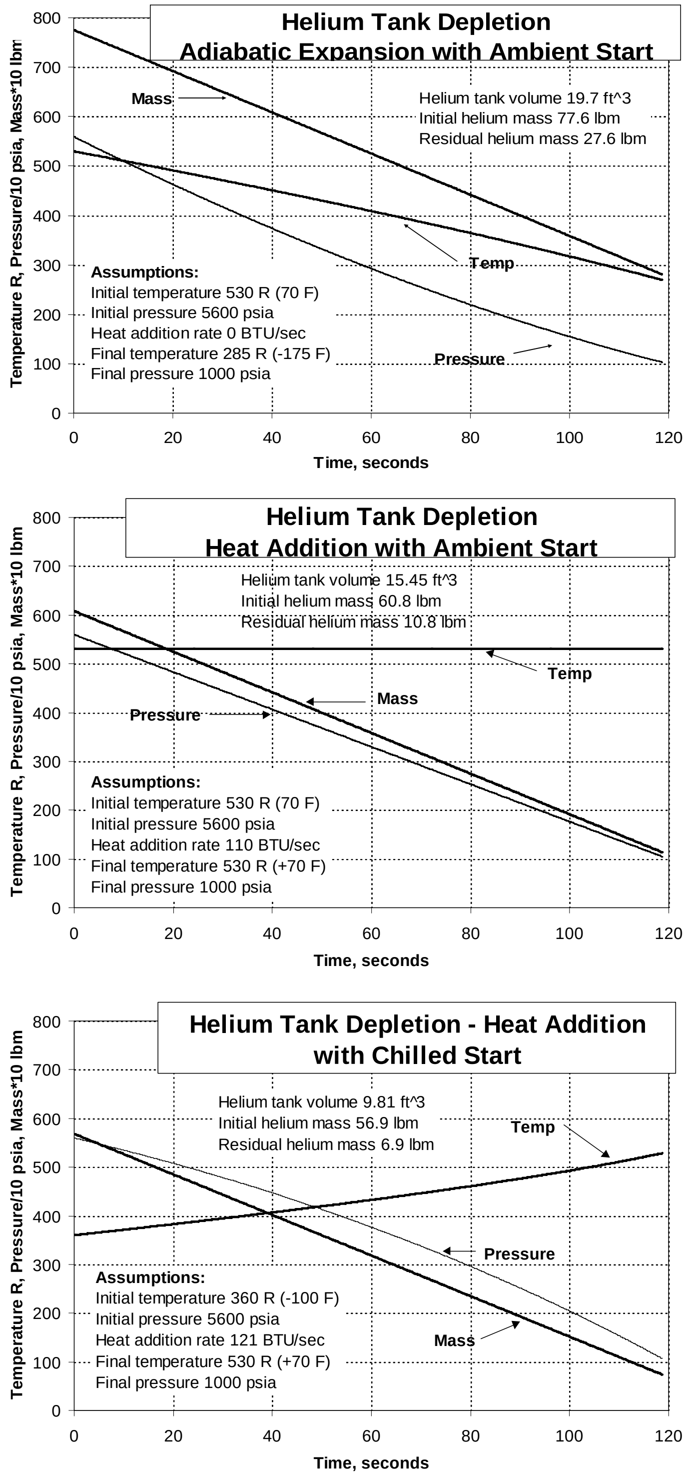

Figure 3. A, B, and C. Pressurant tank pressure, temperature, and helium mass for cold gas vs heated systems

The heated systems of course have the additional advantage of reducing the amount of helium required to maintain pressure in the propellant tanks. Figure 4 compares the helium usage in the liquid oxygen tank for the cold and heated cases. Both heated cases are identical because additional heat is added to maintain the helium supply to the propellant tanks at 200 F. The cold gas system delivers helium at a continuously decaying temperature as the

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pressurant gas expands and cools. The result is that only 35 lbm of pressurant is required to pressurize the LO2 tank for the heated systems, whereas over 50 lbm is required for the cold gas system.

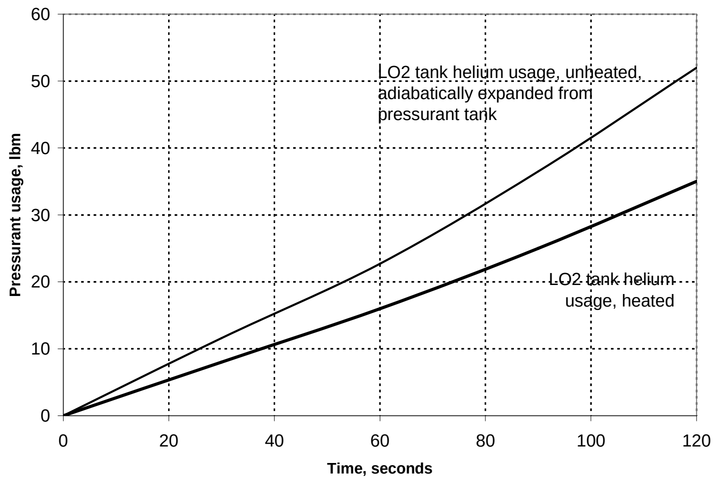

Figure 4. Predicted pressurant usage in LO2 tank – heated vs cold pressurant system

Figure 5 illustrates why less helium is required with heated pressurant gas. This Figure shows axial temperature distribution in the LO2 tank at 75% mission completion (90 seconds following start). Clearly, the much higher average ullage temperature when heated helium is used results in the same tank pressure with less helium mass being required. Although not shown, qualitatively similar results are obtained for the fuel tank.

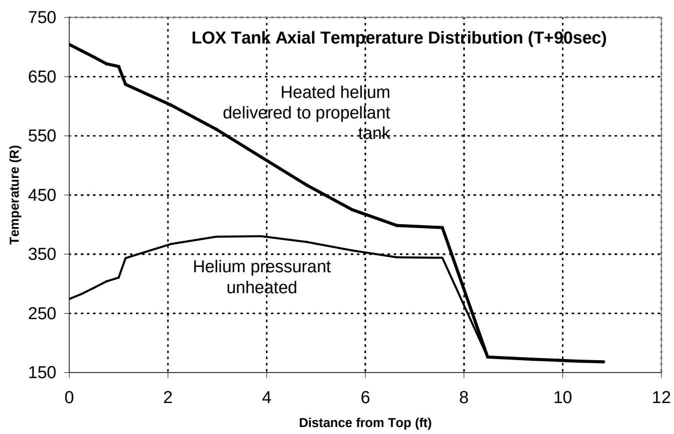

Figure 5. Axial temperature distribution in LO2 tank – heated vs cold pressurant system

II. Design, Development, and Testing of the Tridyne Heated Pressurization System

Chosen baseline configuration

The previously described analysis clearly identifies the advantages of a heated pressurization system that can both supply heat to the pressurant tank (to compensate for expansion cooling), as well as maintain the pressurant temperature as high as practical in the propellant tanks. For the present application (likely typical of other pressure fed vehicles), no source of high pressure autogeneous bleed gas is available for pressurant, and it may be difficult to extract sufficient waste heat from the engine to heat the helium (as might be done, for example, with gas generator exhaust from a turbo pump gas generator).

The proposed solution for this application is to use Tridyne as a heat source for the pressurization system. Tridyne is a weak mixture of hydrogen and oxygen (typically about 1% hydrogen mass fraction) in helium. The mixture will not sustain free combustion at these concentrations, but can be passed through a platinum or palladium catalyst bed and reacted to produce heat.

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At the simplest level, a Tridyne heated pressurization system functions as shown in Figure 6. The reaction is as follows:

$$n\,He + 2\,H_2 + (1 + \varepsilon)\,O_2 \rightarrow n\,He + 2\,H_2O + \varepsilon\,O_2 + heat$$

n is typically between 75 and 150, depending on the energy release required.
ε is the excess oxygen, typically about 0.1 to 0.3.

As molecular diffusion of oxygen appears to be the major rate limiting factor, the excess oxygen allows a smaller catalyst volume to be used. Previous studies (verified by the present work) indicate that mixtures with hydrogen/helium mass fractions below about 4% ($n > 25$) will not sustain free combustion, and are hence considered a safe, non-combustible mixture of gases.

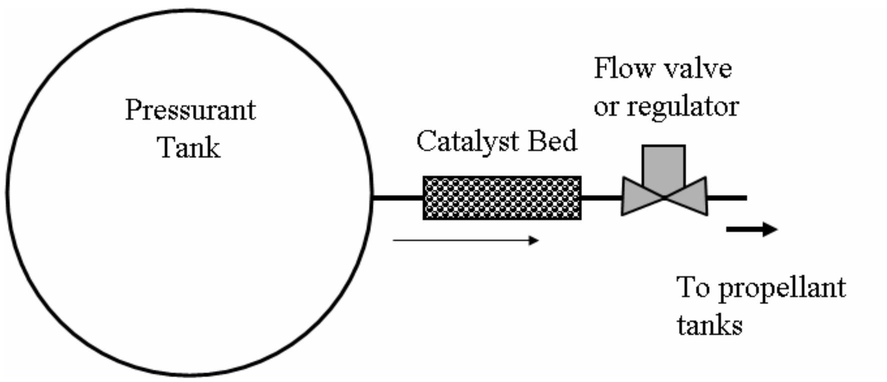

Figure 6. Basic Tridyne pressurization concept

The simple concept shown in Figure 6 does not include a means for supplying any of the generated heat to the pressurant tank contents. Furthermore, the volume of catalyst required to achieve a nearly complete reaction depends primarily on 1) the volumetric flow rate of Tridyne through the system, 2) the geometrical and surface characteristics of the catalyst used, and 3) the temperature of the catalyst and gas mixture at the reaction site. Previous evaluation has indicated that catalyst beds sufficient to produce hot pressurant at rates required for pressure fed launch vehicles may need to be very large if the inlet gas to the catalyst bed is not preheated.

Tridyne systems have been studied in various forms since the 1950's (originating with Rocketdyne in Canoga Park CA, hence the name). Heat exchanger concepts to enhance Tridyne system performance similar to that discussed in this report have been proposed and tested at a "bench level" for decades but, due to reluctance to abandon popular pump fed systems, have not been fully developed and tested for an actual flight application.

Following initial bench testing and trade studies (not presented here), the configuration shown in Figure 7 is chosen for the present application. The catalyst bed and counter-flow heat exchanger are completely internal to the pressurant tank, and the heat exchanger has bi-directional heat transfer in the sense that some of the heat from the catalytic reaction is used to preheat the incoming flow to the catalyst while additional heat is simultaneously transferred to the pressurant tank contents. Specific characteristics and advantages of this configuration are as follows:

1) The catalyst bed and heat exchanger operate with very low differential pressure, hence can be low weight with thin-walled tubing for good heat transfer.
2) Preheating Tridyne prior to the catalyst bed substantially increases reaction rate and reduces the amount of catalyst required.
3) Minimal wasted heat with no insulation (catalyst bed rejects heat directly to pressurant tank contents).
4) Outlet flow at top of tank, feeding heat exchanger inlet, can intercept heat that might otherwise "soak back" from hot side outflow and damage pressurant tank.

Also shown in Figure 7 is a graph indicating typical steady state temperature characteristics as the pressurant proceeds along the flowpath. T_1 is tank temperature and cold-side heat exchanger inlet temperature. T_2 is cold-side heat exchanger outlet temperature and catalyst bed inlet temperature. T_3 is catalyst bed outlet temperature and hot-side heat exchanger inlet temperature. T_4 is hot-side heat exchanger outlet temperature and propellant tank

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pressurant supply temperature. It may be noted that the temperature rise from the tank to the catalyst bed can (and in most cases, should) be greater than the reaction temperature rise across the catalyst

Heat exchanger design is critical, as too much heat transfer could result in the catalyst temperature running above material limits, even though the temperature rise across the catalyst bed is limited by the hydrogen molar fraction of the Tridyne mixture. For the present application, thermal analysis indicates that the correct balance of preheat and tank-heat thermal transfer should occur with a bare tube heat exchanger approximately the length of the tank. For larger vehicle applications (i.e. larger pressurant tanks with higher flow rates), fins might be required on the external tube to increase heat transfer to the tank contents.

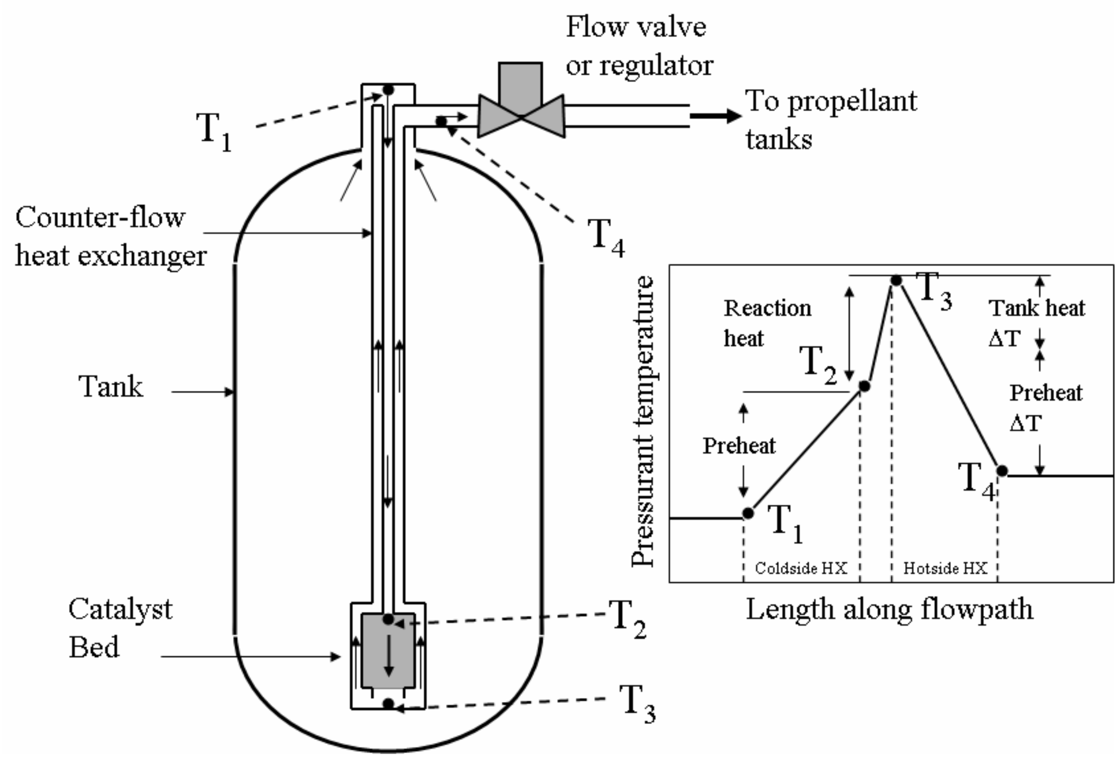

Figure 7. Selected Tridyne catalyst bed and heat exchanger configuration.

Design of integral tank catalyst bed and heat exchanger

The heat exchanger extends approximately 4 feet in length, and is rigidly attached to the top fitting which screws into the upper tank boss. The catalyst bed is supported laterally by engagement into the lower tank flange, but is free to move longitudinally to accommodate differential thermal expansion. Later catalyst beds (not shown) have been increased in diameter (up to 4 inches) to support vehicle designs with much higher pressurant flow requirements.

Description of test apparatus

Figures 8 and 9 show a schematic and photo of one test apparatus built for evaluating catalyst and heat exchanger performance. This apparatus is for evaluation of only the pressurant system performance. It includes capability for dual pressurant tanks and a recirculation system to chill the Tridyne during the loading operation.

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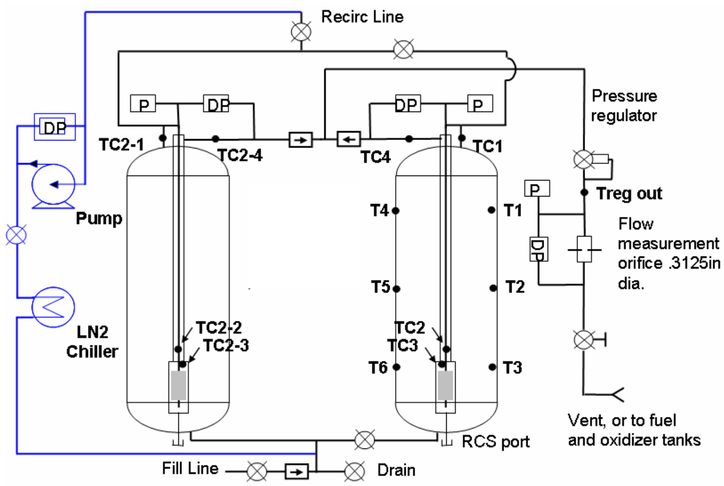

Figure 8. Test apparatus used for dual pressurant tank system evaluation

Figure 9. Photo of pressurant system test apparatus (single, small diameter tank installed)

III. Test Results

More than 50 test runs have been performed to demonstrate system performance with a variety of Tridyne mixture concentrations and starting conditions. Typical results for a test run are shown in Figures 10 and 11. For this run, the Tridyne is loaded at ambient conditions and has a 1.39% hydrogen mass fraction and 30% excess oxygen. This mixture is somewhat "hotter" than a typical application would use, but effectively demonstrates the startup and operating characteristics.

Figure 11 indicates how the heat exchanger, catalyst bed, and outlet temperatures increase when flow is started. Initially, the temperature rise across the catalyst bed is considerably less than what would be theoretically calculated for a complete reaction of the Tridyne mixture. However, the heat release is sufficient to initiate a rise in the catalyst bed inlet temperature, such that the heat exchanger "bootstraps" up to a catalyst bed inlet temperature of approximately 400 to 500 F, and nearly 100% of theoretical heat production, within the first 10 to 20 seconds of operation.

The most critical factor in sizing the catalyst bed is sufficient volume to start the system at maximum initial flow rate. If the catalyst bed is too small, or alternatively the initial flow rate is too high, the initial reaction will be insufficient to overcome the quenching from the flow, and the system will not start. This factor obviously becomes

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more critical at lower initial temperatures. However, experimental results with the initial Tridyne temperature as low as -60 F indicate that reliable startup can be achieved with the catalyst bed only about 30% larger than that required for an ambient start. The 3.5 inch catalyst length shown in Figure 7 and used in the ambient start tests is found to be slightly shorter than optimal, especially for chilled systems. Later results indicate that 4 to 6 inch catalyst length is desirable. Reliable starts with smaller volume catalyst beds can be achieved by drawing at a reduced flow rate for 10 to 20 seconds (to preheat the catalyst bed) before switching to full flow. A reduced initial flow rate may also be necessary if water is frozen in the catalyst bed from previous operation. Surprisingly, the system always starts reliably with a 10 to 20 second reduced lead flow, even when the catalyst bed is known to contain frozen water.

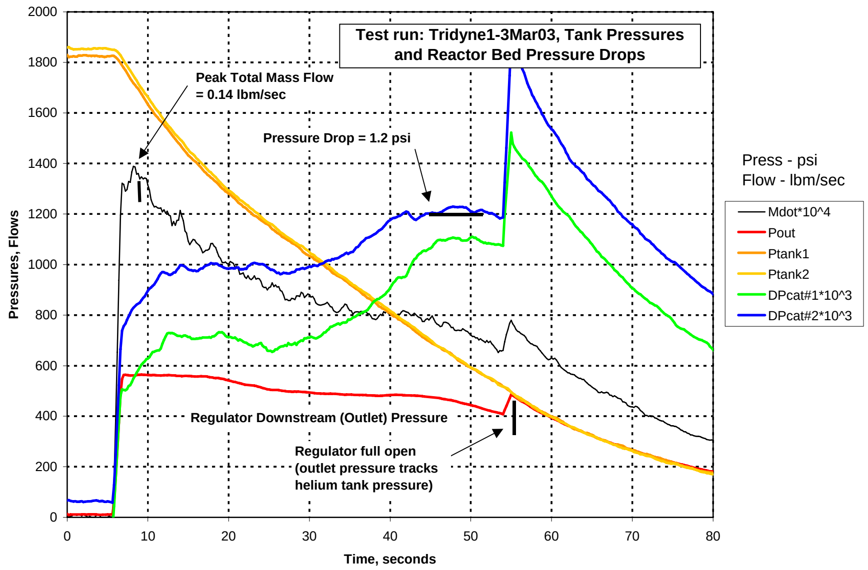

Figure 10. Temperature and pressure and catalyst bed differential pressure measurements for typical Tridyne test (Run 1 – 3Mar03)

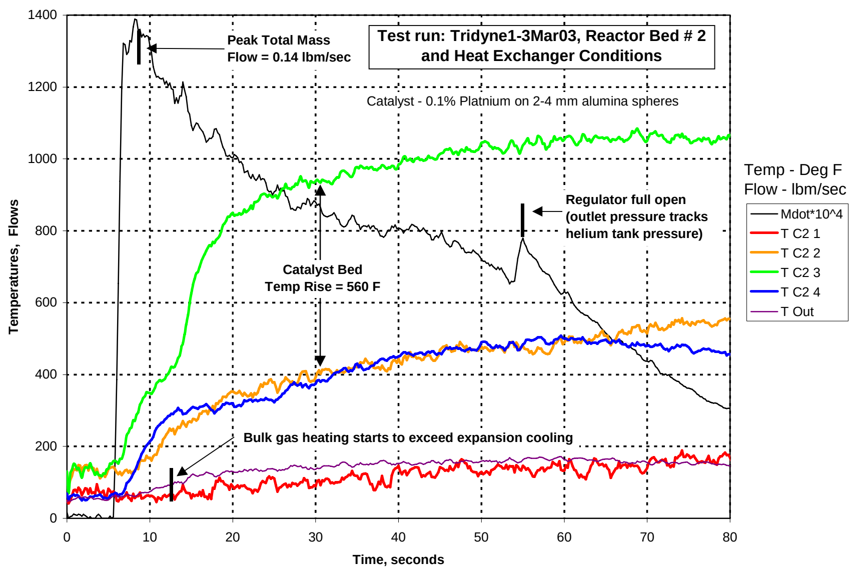

Figure 11. Temperature measurements across heat exchanger and catalyst bed

Follow-on liquid expulsion testing

Later testing (Figures 12 and 13) include a cryogenic liquid expulsion tank (simulated propellant tank) to allow evaluation of the entire pressurant and propellant feed operation. The expulsion test apparatus also allows evaluation of issues such as pressurization diffuser design and what effects the water (generated from the reaction) might have on the overall vehicle operation.

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For optimal overall system performance, the design of the diffuser in the propellant tank becomes very important with a heated pressurization system. The pressurant gas must remain stratified and hot within the propellant tank. If the diffuser does not dissipate the flow velocity sufficiently, heat transfer to the cold tank walls and the liquid surface will defeat the advantage of the heated system.

The expulsion tank outlet includes a simulated engine injector plate to assess the risk of water (from the Tridyne reaction) freezing and plugging the injector. Tests performed with liquid nitrogen (in which water ice sinks) indicate that injector plugging can occur. However, repetitive testing performed with liquid oxygen (in which water ice floats) confirms that no ice reaches the injector until the tank is depleted.

Additional work using desiccants to remove residual water indicate that these systems can be very effective. The desiccant configuration evaluated uses the diffuser as a reservoir for the desiccant material. However, results indicate that the initial desiccant weight must be at least 4 to 5 times greater than the mass of water that must be removed. Hence, the weight impact of a desiccant system is substantial and significantly detracts from the overall pressurant system weight savings that is otherwise achieved with Tridyne.

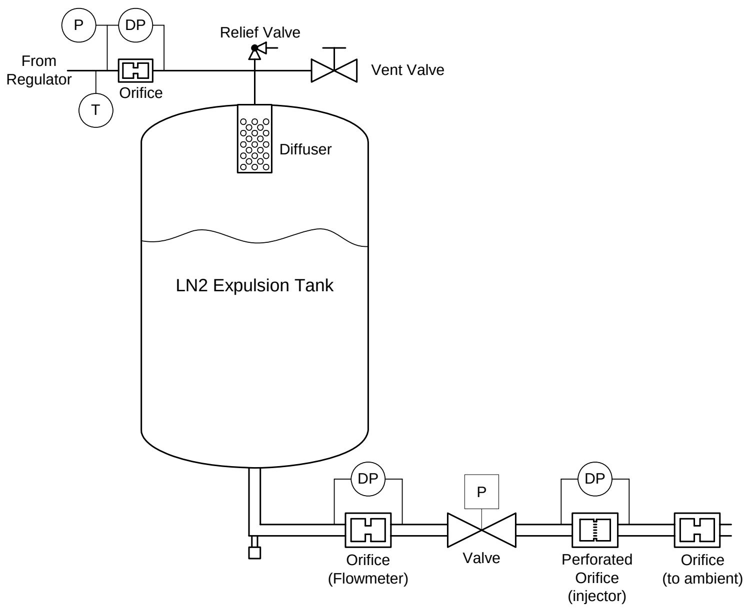

Figure 12. Schematic of expulsion tank and simulated engine injector added to Tridyne test apparatus for expulsion testing

Figure 13. Photo of simulated propellant tank used for expulsion testing

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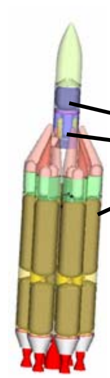
IV. Payload Performance

The test results substantiated our analytical prediction that the pressurization system mass reduction of 50% can be realized compared to a cold-gas pressurization system. Figures 14 (a,b) show the performance gain when the Tridyne-based HPPS is incorporated in the two orbital launch vehicles with capability of 2000 lbm and 20,000 lbm to LEO. These two launch vehicles are derivatives of the Liberty and the Exodus launch vehicles in Mocrocosm's Scorpius family.



Liberty-RO Vehicle Comparison

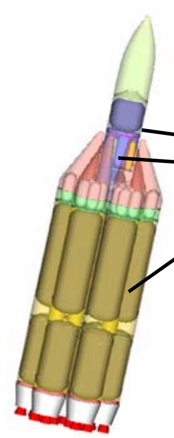
	Tridyne		Cold Gas		Advantage	
	mass (lb)	cost	mass (lb)	cost	mass (lb)	cost
Stage 3	117	36,721	166	45,802	49	9,081
Stage 2	553	36,844	1,290	39,926	737	3,082
Stage 1 (pod)	533	42,105	1,265	33,258	732	-8,848
Total Vehicle	3,868	326,198	9,043	285,274	**5,175**	**-40,924**

Payload savings (lb)

	Ratio to 1lb of payload	Increased Payload (lb)
Stage 3	1	49
Stage 2	6	123
Stage 1 (stage)	36	132
Total Saving		304

Payload increase **304 lb** **(15.2% for 2,000lb)**
Cost increase **$41,000***
Vehicle length decrease **70 in** **(8.7% LOA: 804 in)**

*cost based on production vehicle



Exodus-RO Vehicle Comparison

	Tridyne		Cold Gas		Advantage	
	mass (lb)	cost	mass (lb)	cost	mass (lb)	cost
Stage 3	1,125	56,401	1,628	65,934	503	9,533
Stage 2	6,211	241,867	13,194	202,948	6,983	-38,919
Stage 1 (pod)	6,033	253,275	12,942	192,370	6,909	-60,905
Total Vehicle	43,536	1,817,918	92,476	1,423,103	**48,940**	**-394,815**

Payload savings (lb)

	Ratio to 1lb of payload	Increased Payload (lb)
Stage 3	1	503
Stage 2	6	1164
Stage 1 (stage)	36	1152
Total Saving		2819

Payload increase **2819 lb (14.1% for 20,000lb)**
Cost increase **$395,000***
Vehicle length decrease **143 in (7.6% LOA: 1,886 in)**

*cost based on production vehicle

Figure 14 a: Liberty –RO Payload gain, 16 b: Exodus-RO Payload gain due to HPPS

V. Conclusions

Work discussed in this paper verifies that a Tridyne heated pressurization system with integral heat exchanger for catalyst bed preheating and pressurant tank heating is practical and effective. Using a Tridyne pressurization system as described, it is realistic to expect a 50% reduction in pressurant system mass compared to a cold gas (helium only) system.

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For single burn, expendable vehicle, applications, the water generated by the Tridyne reaction should pose no problem, since testing indicates that any water condensing in the oxidizer tank will float on the liquid surface and not affect engine operation.

For multiple burn or reusable applications, water in the pressurant would likely cause problems with cryogenic vent valves, risk of engine ingestion, or other component issues. For these applications, a desiccant can be used to remove most of the water, but with significant weight penalty and some added complexity. Hence a Tridyne system is less desirable for these applications.

References

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[2] Chakroborty, S., Wertz, J.R., Conger, R, and Kulpa, J. "The Scorpius Expendable Launch Vehicle Family and Status of the Sprite Small Launch Vehicle," *AIAA 1st Responsive Space Conference*, Redondo Beach, CA, April 1-3, 2003.

[3] Chakroborty, S., Bauer, T., "Using Pressure-Fed Propulsion Technology to Lower Space Transportation Costs," *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 11-14 July 2004, Fort Lauderdale, Flordia.

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